Pavement Strain from Moving Dynamic 3D Load Distribution

By Raj V. Siddharthan,[1] Member, ASCE, Jian Yao,[2] Student Member, ASCE, and Peter E. Sebaaly,[3] Member, ASCE

(Reviewed by the Highway Division)

Abstract: This paper presents the formulation and the application of a continuum-based finite-layer approach to evaluate pavement strain response under actual traffic loading. The model incorporates important pavement response parameters such as the dynamic tire-pavement load variations and corresponding complex contact stress distributions (normal and shear), vehicle speed, and viscoelastic material characterization. Results of a parametric study in which two typical thin and thick pavement sections were subjected to traffic loading moving at different speeds are included. As an important application of the proposed method, pavement strain responses generated by wide-base and dual tires have been presented. This study reveals that contradictory to the past studies, the impact of tire-pavement contact shear stress on tensile strain at the bottom of asphalt concrete is insignificant.

INTRODUCTION

Mechanistic procedures to compute pavement response have been evolving since they received widespread attention at the First International Conference on Structural Design of Asphalt Pavements in 1962. Such procedures provide the means by which the pavement response in terms of stresses, strain, and deflections in a multilayer pavement system can be estimated when subjected to vehicle-induced loads. Many of the widely used pavement analysis procedures, including the recent Strategic Highway Research Program Superpave performance models use the pavement response as a critical input. Characteristics of vehicle loading, pavement materials, and method of construction have been undergoing many changes over the years. For example, the tire pressures have increased to >760 kPa from 520 kPa used in the 1960s. Wide-base (super single) tires are being proposed to replace the traditional dual tires. New pavement materials, such as modified asphalt concrete (AC) mixtures and open-graded AC rather than dense-graded mixtures, are becoming common. The mechanistic procedures enable the pavement engineer to accommodate many of these changes in a more fundamental way.

The tire-pavement interaction is quite complex; the loaded area is noncircular, with nonuniform normal as well as substantial contact shear stress components. Furthermore, the tire load that gives rise to the complex contact stress distribution is a moving load that varies (i.e., dynamic) as it traverses the pavement. Past studies and other research on the characteristics of the tire-pavement interaction load resulting from a moving truck reveal that it is strongly governed by three important factors: (1) Road roughness; (2) vehicle speed; and (3) truck suspension system (Leblanc and Woodrooffe 1995; Streit et al. 1995).

The success of a mechanistic procedure mainly depends on how realistically it can model the tire-pavement interaction loading and pavement material behavior. Many widely used mechanistic procedures are much simpler (e.g., ELSYM5, BISAR, etc.); they treat the tire interaction as static, uniform, and stationary circular loads. The influence of either the moving or dynamic nature of the interaction loading or contact shear stresses is seldom considered. More recent studies have attempted to model the pavement loading more realistically (Sousa et al. 1988; Papagiannakis et al. 1996). However, as will be seen later, these approaches suffer from many limitations.

The model described in this paper is a moving load model, which advances significantly the work by Siddharthan et al. (1993) and Zafir et al. (1994). It is capable of predicting pavement response (strain, stresses, and deflections) and treats the tire-pavement interaction as a moving loaded area. It also approximately accounts for the dynamic nature of the moving load. It is a continuum-based finite-layer approach that uses the Fourier transform technique; therefore, it can handle complex surface loadings such as multiple loads and nonuniform tire-pavement contact stresses (normal and shear). The tire imprint can be of any shape, thus making this model suitable to analyze wide-base tires. The proposed method is much more computationally efficient than the moving-load models based on the finite-element method (Huhtala and Pihlajamäki, 1992). The AC layer is treated as viscoelastic, in which the properties (complex shear modulus and Poisson's ratio) can vary as a function of frequency. In the current model, the base course and the subgrade are considered linear elastic.

The use of wide-base tires is becoming widespread in recent years because their application offers a significant economical advantage to the trucking industry. Therefore, national and international efforts are underway to quantify the pavement damage caused by use of wide-base tires. This paper focuses on providing pavement response for the case of wide-base tires. For comparison, response from a conventional tandem axle dual tire configuration is also presented.

EXISTING METHODS OF DYNAMIC PAVEMENT RESPONSE

When a truck, moves on a pavement, it exerts loads that vary in space and time. The conventional pavement analysis models (e.g., ELSYM5) that assume the loads as static and stationary completely ignore the moving nature of the load. Pavement responses measured in the field have clearly indicated that the speed of a vehicle affects the pavement strain response (Akram et al. 1992; Sebaaly and Tabatabaee 1993). In general, there are two important factors that should be considered in any dynamic pavement analysis: (1) The variation of the interaction load with time and space; and (2) the dependency of the material properties on the applied stress and

[1]Prof., Dept. of Civ. Engrg., Univ. of Nevada, Reno, NV 89557.
[2]Grad. Student, Dept. of Civ. Engrg., Univ. of Nevada, Reno, NV.
[3]Assoc. Prof., Dept. of Civ. Engrg., Univ. of Nevada, Reno, NV.

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the loading frequency. Monismith (1992) and Thompson (1996) provide a comprehensive review of various mechanistic procedures and their limitations. A vast majority of the procedures suffer from the inability to model many of the following important conditions: noncircular and multiple loaded areas, time-varying normal and shear contact stresses, and stress- and rate-dependent material properties. The few approaches that have attempted to model the dynamic nature of the pavement loading are critically reviewed subsequently.

Recently, some researchers have considered the stress- and frequency-dependent material properties in the pavement analysis procedures (Chen 1987; Sousa et al. 1988; Huang 1993). The computer program, KENLAYER, based on Burmister's layered theory, solves for an elastic multilayered system under stationary single or multiple circular loaded areas (Huang 1993) with uniform and normal pressure. The AC layer can be treated as linear elastic or viscoelastic. The base and the subgrade can be divided into several sublayers, and the stress-dependent moduli are estimated for each sublayer through an iterative procedure. The moduli vary in the vertical direction but remain constant along the horizontal plane for each sublayer.

A computer program called SAPSI, developed by Monismith and his coworkers (Monismith 1992; Sousa et al. 1988) can be used to compute the dynamic response of a viscoelastic layered system subjected to stationary disk (circular) loads. A similar approach was advanced recently by Papagiannakis et al. (1996). Multiple loadings can be analyzed, and each loading may have a different loading area and time history.

In these methods the load-time history on the loaded areas varies as a function of the velocity of the moving vehicle. The response under a moving load is determined through an equivalent approach, in which it has been assumed that the response of a point at a distance x from a moving load is equal to the response of another point at the same distance x from a stationary load. The approach is identical to the one proposed by Sebaaly and Mamlouk (1987). These methods suffer from the following limitations: (1) Since they use stationary loaded area(s), they do not account for the true nature of the moving load; (2) because an axisymmetric formulation is used, consideration of noncircular (e.g., wide-base tires) is impossible; (3) only the variation in tire-pavement contact stresses (normal and shear) that conform to the axisymmetric condition can be used; and (4) it is required to specify a time history of loading on the stationary circular plate that depends on vehicle velocity. In addition, the assumption that a uniform pressure is present over the entire stationary loaded areas even when a tire occupies only a part of the loaded area is questionable. This issue becomes more important, especially in the case of flexible pavements, since the size of loaded area and the thickness of the AC layer have the same order of magnitude.

Three-dimensional (3D) finite-element-based models have also been proposed for pavement analysis (Huhtala and Pihlajamäki 1992; Sousa et al. 1993). Limitations associated with such methods are well known, and they include substantial computational effort and the errors resulting from the need to incorporate artificial lateral boundaries. Hardy and Cebon (1993) used a well-known convolution integral to study the pavement response to a moving load. A major limitation of this method is that the measurement of pavement response (e.g., longitudinal strain response) must be known a priori, for instance, for impact loading.

Siddharthan et al. (1993) and Zafir et al. (1994) reported on the formulation of a continuum-based finite-layer approach to evaluate the response of a pavement subjected to a moving traffic load. In their approach the pavement layer system is characterized using horizontal layers, each with a set of uniform properties. The layers can be either viscoelastic or elastic. Their model is based on the more efficient finite-layer approach in which only rectangular moving loads and variation in contact stresses in the longitudinal (vehicle direction) can be handled. This is because they modeled the loaded area as a thin strip with two special viscous boundaries (front and back) parallel to the longitudinal direction. Such a representation cannot model the variation of normal or shear stresses in the transverse direction. Furthermore, their approach does not account for the dynamic variation (time and space) of the moving load.

PROPOSED APPROACH

Problem Definition and Characterization of Dynamic Moving Load

Fig. 1 presents a sketch of a pavement structure subjected to a moving traffic load. The pavement structure consists of horizontal layers, each defined by a set of uniform properties. It is required to find the response (stress, strain, or displacement) at any Point A, as the moving load traverses the pavement with uniform velocity V. Initially, the load is at some distance (Point O) far away from the plane of observation (Fig. 1). The axes, which go through O are as shown in the figure: The x-axis is along the wheel path (longitudinal), the z-axis is vertical, and the y-axis is perpendicular to the wheel path (transverse). Though only a single loaded area is shown in the figure, the load can consist of multiple loads with each having any contact stress (normal and shear) distributions on the x- and y-plane.

Fig. 2 presents the elevation view and a sketch of a typical longitudinal strain, ε_x response at A. As the load moves from O, the tire-pavement interaction load $P(x)$ varies with distance (or time) as shown. This interaction force, $P(x)$ may be characterized as having a mean ($\bar{P}$) and an additional varying component $\tilde{P}(x)$, which represents the perturbation (variation) of the force about the mean (Fig. 2). In other words

$$P(x) = \bar{P} + \tilde{P}(x) \tag{1}$$

Many theoretical and experimental tire-pavement interaction studies have revealed that the component $\tilde{P}(x)$ is strongly influenced by the vehicle suspension system, road roughness, and speed of vehicle. State-of-the art reports on quantifying $\tilde{P}(x)$ have been presented by Gillespie et al. (1993) and Streit et al. (1995).

When the load is at a large distance (at O; $x = 0$), there is no strain response at A, but as the load moves toward A, there is response as shown in Fig. 2. When the load is at B ($x = x_0$),

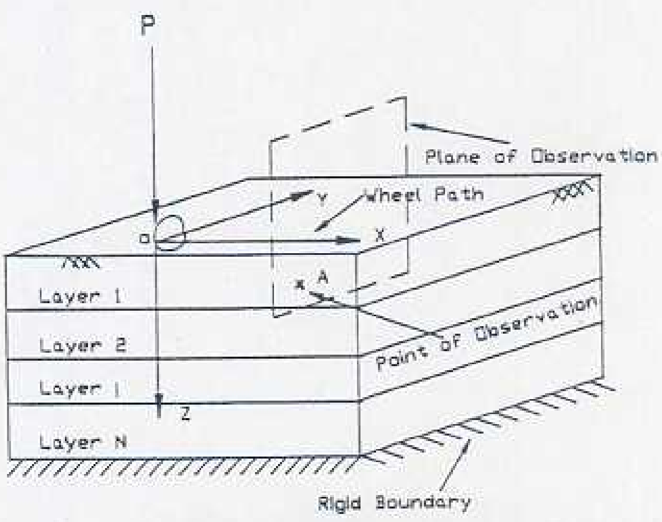

FIG. 1. Problem Definition: Moving Load Induced Response

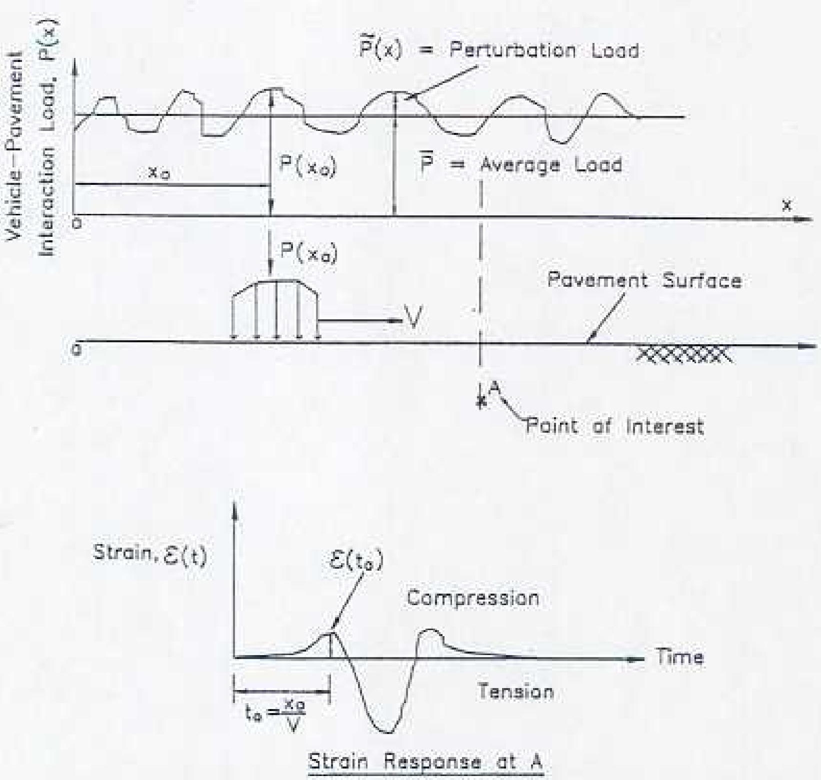

FIG. 2. Elevation View of Moving Load and Corresponding Strain Response at A

after a time t_0 given by $t_0 = x_0/V$, the strain response is $\varepsilon(t_0)$. At this time, the applied load is $P(x_0)$. Similar to (1), the strain response at t_0 may also be assumed to be given by

$$\varepsilon(t_0) = \bar{\varepsilon}(t_0) + \tilde{\varepsilon}(t_0) \tag{2}$$

in which $\bar{\varepsilon}(t_0)$ = response at A caused by the average load $\bar{P}$; and $\tilde{\varepsilon}(t_0)$ = response component due to perturbation component $\tilde{P}(x)$ at B. Since the magnitude of $\tilde{P}(x)$ relative to $\bar{p}$ is small and the system is linear, it is reasonable to assume that the strain response components at A are proportional to the corresponding load components at B. This means that (2) can be rewritten as

$$\varepsilon(t_0) = \bar{\varepsilon}(t_0) + \bar{\varepsilon}(t_0)*\tilde{P}(x)/\bar{P} \tag{3}$$

It may be argued that since the change in load also results in change in loaded area, the proportionality assumed between the load and the strain may not be justified. However, field measurements of pavement strain response compiled by a Federal Highway Administration study using the Accelerated Loading Facility (ALF) located in McLean, Va., supports this assumption (Bonaquist 1992). This study reveals that in the case of two typical pavements (AC layer thicknesses of 89 and 178 mm) for vehicle loads varying between 40 and 70 kN, the strain response was proportional to the applied load. In these tests the tire pressure was kept constant at 703 kPa, and the measured strain reponses were longitudinal strain at the bottom of the AC layer and compressive strain at the top of the subgrade. Both wide-base and dual tire configurations were used in this study. It may also be noted that a similar assumption was made by Markow et al. (1988).

This means that if the mean response $\bar{\varepsilon}(t_0)$ and the perturbation of the tire-pavement interaction load are known, the strain response can be evaluated using (3). Since perturbation of the interaction load as a function of vehicle suspension system, road roughness, and vehicle speed has been quantified well in past studies, attention in this paper will be first devoted to the characterization of $\bar{\varepsilon}(t_0)$. From now on, the text does not include the bar symbol because it is understood that the formulation presented is for the mean load.

Governing Equations

The normal stress σ_{zz} and shear stress components τ_{xz} and τ_{yz}, which characterize a contact surface pressure moving at a velocity V in the longitudinal x-direction can be written as

$$\sigma_{zz} = \sum_{n=1}^{N} \sum_{m=1}^{M} B_{mn} e^{i\lambda_n(x-Vt)} e^{i\mu_m y} \tag{4a}$$

$$\tau_{xz} = \sum_{n=1}^{N} \sum_{m=1}^{M} C_{mn} e^{i\lambda_n(x-Vt)} e^{i\mu_m y} \tag{4b}$$

and

$$\tau_{yz} = \sum_{n=1}^{N} \sum_{m=1}^{M} D_{mn} e^{i\lambda_n(x-Vt)} e^{i\mu_m y} \tag{4c}$$

where B_{mn}, C_{mn}, and D_{mn} = Fourier coefficients; and λ_n and μ_m = corresponding wavelengths of the harmonics. These are the result of the Fourier expansion of the contact pressure distribution on the loaded area, and N and M are the number of harmonics considered. It should be noted that the Fourier expansion can be used to represent a load distribution of any shape, and it implies that the applied load variation is periodic. The load specification [(4a)–(4c)] will be selected with a sufficient "quiet zone" at the end of the loaded area to allow time for the damping of the system to attenuate the response from one cycle before the beginning of the next cycle.

The response for a linear or viscoelastic system (for instance, the horizontal displacement u) at any point is then given by the algebraic sum of the harmonics giving

$$u = u(x - Vt) = \sum_{n=1}^{N} \sum_{m=1}^{M} U_{nm}(z) e^{i\lambda_n(x-Vt)} e^{i\mu_m y} \tag{5}$$

in which $U_{nm}(z)$ reflects the variation in displacement of u with z only for the nth and mth harmonics. The major advantage in writing the response in this fashion is that the derivatives with respect to x, y, and t are straightforward; thus, any response can be written in terms of z only (Siddharthan et al. 1993). Under these circumstances, if the response to a single harmonic can be found, then the principle of superposition can be used to obtain the pavement response as an algebraic sum of the contributions from all the harmonics present.

Solution for Single Harmonic Pressure

Dynamic equations of motion for a 3D elastic continuum can be written using index notation (Timoskenko and Goodier (1970) as

$$\sigma_{ij,j} = -\rho \frac{\partial^2 u_i}{\partial t^2} \quad (6)$$

in which σ_{ij} = stress tensor; ρ = mass density; and u_i = displacement in the ith direction. The comma that appears between ij and j represents differentiation with respect to the direction j. According to Timoshenko and Goodier (1970), the elastic stress-displacement relationships in index notation can be written as

$$\sigma_{ij} = M\delta_{ij}u_{k,k} + G(u_{i,j} + u_{j,i}) \quad (7)$$

in which δ_{ij} = Kronecker delta; and M and G are Lamb's constants. Substituting (7) into (6) results in three equations in terms of three unknown displacements. Therefore, the solution of the problem is possible.

Knowing that the response will be in the form given in (5) for each harmonic, steps similar to those followed by Siddharthan et al. (1993) and Zafir et al. (1994) will lead to a sixth-order ordinary differential equation

$$D_1 \frac{d^6 U_{nm}}{dz^6} + D_2 \frac{d^4 U_{nm}}{dz^4} + D_3 \frac{d^2 U_{nm}}{dz^2} + D_4 U_{nm} = 0 \quad (8)$$

in which D_1–D_4 = constants that depend on layer material properties, velocity of vehicle, λ_m, and μ_m. It can be shown that the solution for this differential equation is of the form

$$U_{nm} = B_1 e^{-n_1 z} + B_2 e^{n_1 z} + B_3 e^{-n_2 z} + B_4 e^{n_2 z} + B_5 z e^{-n_2 z} + B_6 z e^{n_2 z} \quad (9)$$

in which n_1 and n_2 = constants that depend on material properties and wave numbers; and B_1–B_6 = integration constants.

In the case of horizontally layered deposits with different properties, an equation similar to (9) exists for every layer. Therefore, altogether there are constants (B_j) that total six times the number of layers. These constants can be evaluated by satisfying the top and bottom boundary conditions, interface continuity conditions in displacement, and normal and shear stresses (Siddharthan et al. 1993; Zafir et al. 1994). After solving for these constants, the response in terms of displacements, stresses, and strains can be obtained at any point within the pavement. Then the solution for the wheel loading is obtained by summing the responses computed for all of the harmonics.

A computer code 3D-moving load analysis (3D-MOVE) has been developed incorporating the preceding solution technique. This program can handle any number of layers with any type of load distribution at the surface. The higher the number of layers, the larger the computational effort. At present, the code is capable of incorporating frequency-dependent properties of AC layer while base course and subgrade layers are treated as linear elastic. There is no limit to the number of horizontal layers that can be considered by the program. The characterization used for the AC layer in the proposed study is presented subsequently. The nonlinear stress-dependent response of the base course and subgrade is not considered in this paper. Research is underway to account for this effect.

MATERIAL CHARACTERIZATION

Sousa and Monismith (1987) studied the effects of different parameters on dynamic modulus of AC. The AC samples were tested under three different temperatures of 11, 25, and 40°C and were subjected to sinusoidal cyclic axial and torsional loading with varying frequencies. They found that for AC, the amplitude of the dynamic complex shear modulus $|G^*|$ is a strong function of temperature and frequency of the loading. The variation in the dynamic AC shear modulus at various temperatures with loading frequency is shown in Fig. 3(a). It shows that the dynamic shear modulus of AC increases with the increase in loading frequency. The variation in dynamic Poisson's ratio with frequency is shown in Fig. 3(b). Unlike the dynamic shear modulus, the Poisson's ratio decreases with frequency.

Two fundamentally different damping phenomena are associated with pavements, namely, material damping and radiation damping. Material damping is due to internal energy dissipation, while radiation damping is a measure of the energy loss associated with the radiation of waves away from the region of interest. For engineering applications, the internal damping of the pavement materials can be included in the analysis by writing the modulus in its complex form as follows (Rosset 1980; Sousa and Monismith 1987):

$$G^* = G(1 + 2i\zeta_{AC}) \quad (10)$$

in which G^* = complex dynamic shear modulus; and ζ_{AC} = measure of internal damping of the AC.

For viscoelastic layers, the shear modulus G that appears in (7) is replaced with its complex form given by

$$G^* = G_1 + iG_2 \quad (11)$$

in which G_1 and G_2 = real and imaginary shear modulus components. From (10) it may be deduced that

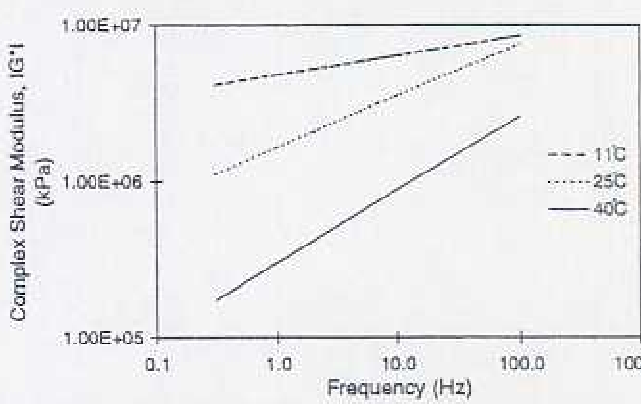

FIG. 3(a). Variation of Complex Shear Modulus with Frequency and Temperature (after Sousa and Monismith 1987)

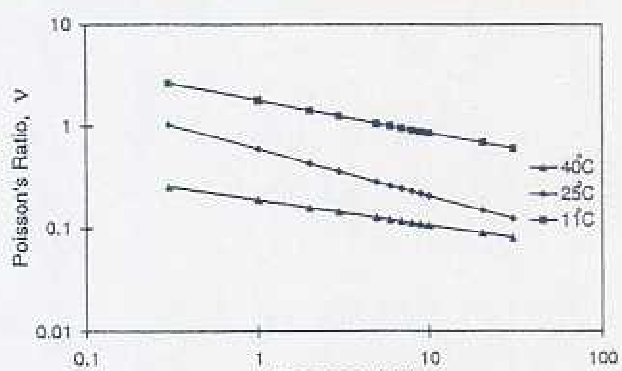

FIG. 3(b). Variation of Poisson's Ratio with Frequency and Temperature (after Sousa and Monismith 1987)

$$G_1 = \frac{|G^*|}{\sqrt{1 + 4\zeta_{AC}^2}} \quad \text{and} \quad G_2 = 2G_1\zeta_{AC} \qquad (12a,b)$$

In this study, the values of $|G^*|$ shown in Fig. 3(a) and ζ_{AC} = 5% have been used to define the behavior of the AC. It may be noted that the angular frequency of each harmonic is $\lambda_n V$ from (5). In elastic analyses, the energy consideration requires that the Poisson's ratio be between 0 and 1/2. Therefore, the Poisson's ratio variation shown in Fig. 3(b) was assumed to be valid only between 0.01 and 0.495.

Since the proposed model is a "finite-layer" model, it is incapable of considering the changes in modulus within a layer in the lateral direction. Therefore, the properties of stress sensitive materials such as base and subgrade may be treated as a number of linear elastic sublayers with constant modulus (without variation in lateral direction). This type of characterization has been successfully used in other computer models such as KENLAYER (Huang 1993) and EVERSTRS (Sivaneswaran et al. 1996).

The shear modulus and the internal damping for the base and subgrade layers can be included in the analysis in the same fashion as for the AC layer [(10)]. The internal damping of the unbound layers also has been assumed to be 5%. It may be noted that, since the entire domain has been treated as layers extending to infinity in the lateral direction (i.e., without any artificial lateral boundaries), the radiation damping has been implicitly incorporated into the proposed analysis.

VERIFICATION OF PROPOSED APPROACH

There are a number of classical solutions against which the applicability of the proposed method and the ensuing computer program (3D-MOVE) can be verified. Of course, the classical solutions are available only for many simplified conditions. Three well-known classical solutions have been used in the verification: (1) Fung's (1965) solution for elastic half-space subjected to harmonic surface pressures; (2) Ueshita and Meyerhof's (1968) solution for rectangular loaded area with uniform pressure on a layer of finite thickness; and (3) Ahlborn's (1972) solution for circular loads with uniform pressure on a multilayered system (ELSYM5). Since ELSYM5 is one of the widely used programs in pavement studies, the verification using this program only is presented next.

The solution technique used in ELSYM5 is based on Burmister's elastic layer theory, while the Fourier transform technique along with finite-layer formulation is used in this study. Therefore, validation using ELSYM5 may be considered an independent check. Furthermore, this validation using ELSYM5 will verify the capability of 3D-MOVE to simulate the circular loaded area and its ability to combine layers with different material properties.

Fig. 4(a) shows a pavement layer system subjected to loads from a single axle dual-tire configuration. The load per tire and the tire pressure are 22.5 kN and 862 kPa, respectively. This loading results in two circular tire imprints with a 0.182-m diameter as shown. Though any pavement responses such as stress, strain or displacement may be compared, the normal strain in the longitudinal direction ε_x and transverse direction ε_y at the bottom of the AC layer along the transverse direction (along x = 0) was selected for comparison. This is because these normal strain components are often critical input in the evaluation of fatigue life of AC pavements. Fig. 4(b) shows the computed results from ELSYM5 and 3D-MOVE. The re-

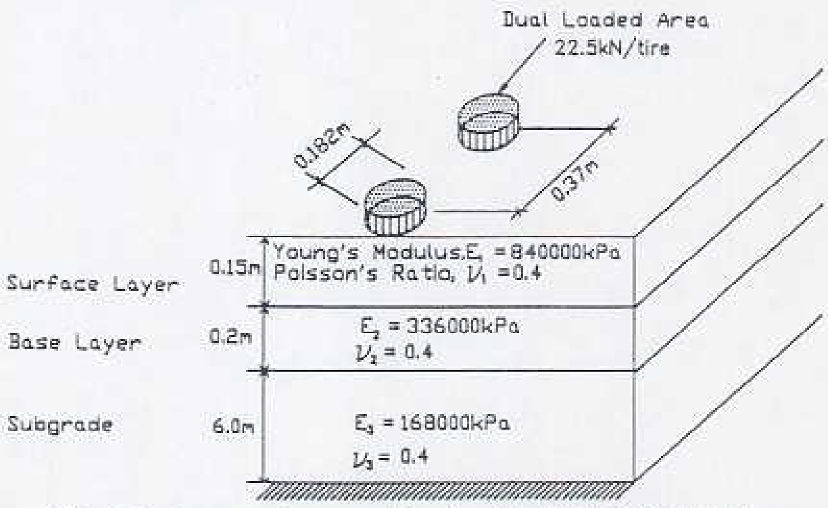

FIG. 4(a). Pavement Layers and Loading Used in ELSYM5 Validation

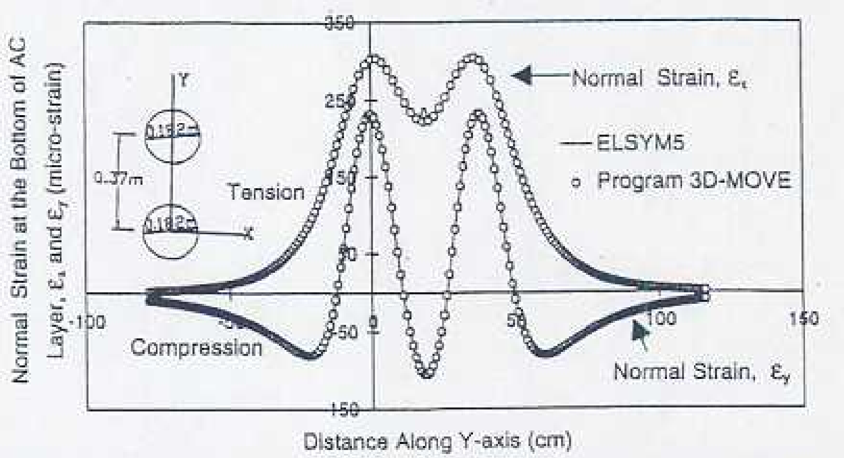

FIG. 4(b). Normal Strain Responses from Program 3D-MOVE and ELSYM5 sults are virtually identical, indicating that the 3D-MOVE is capable of simulating correctly the static circular loads applied to a layered system.

APPLICATION TO FIELD PROBLEMS

Description of Example Problem

To illustrate the application of the proposed approach, two different pavements, representing a thin and a thick pavement were subjected to loading from a moving tandem axle. Figs. 5(a and b) show the pavement layer thicknesses and a sketch of the moving tandem axle loading. The physical material properties of base and subgrade, which were assumed elastic, are given in Table 1. The pavement layer configuration is similar to the pavement sections tested in the field instrumentation study reported by Sebaaly and Tabatabaee (1993). The dynamic material properties of the AC layer were assigned from

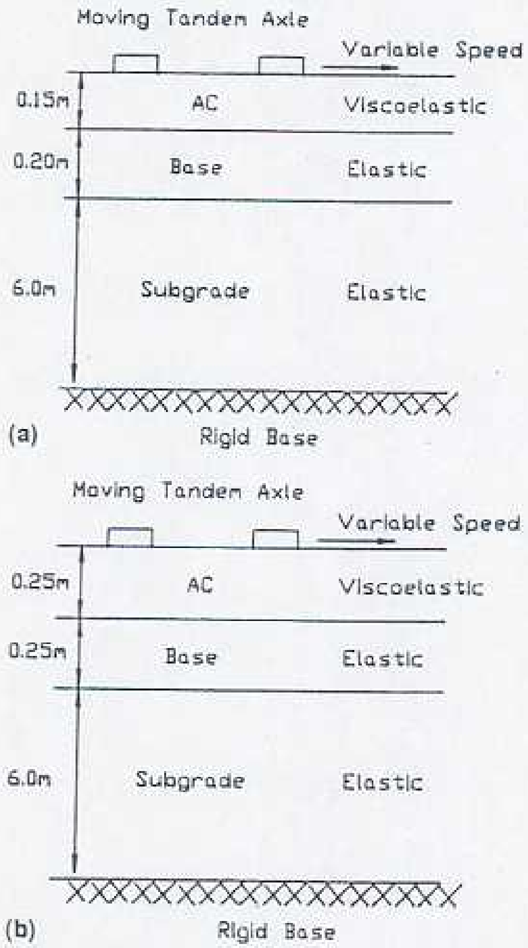

FIG. 5. Pavement Structure Properties: (a) Thin Pavement; (b) Thick Pavement

TABLE 1. Properties of Layers Used in Parameter Study

Layer (1)	Thickness (m) (2)	Unit weight (kN/m^3) (3)	Shear modulus (kPa) (4)	Damping ratio (%) (5)	Poisson's ratio (6)
AC	0.15 and 0.25	22.8	Variable[a]	5	Variable[b]
Base	0.20 and 0.25	19.6	7.5×10^4	5	0.35
Subgrade	6.0	17.3	3.0×10^4	5	0.40

[a]Assumed to vary as given in Fig. 3(a) (T = 40°C).
[b]Assumed to vary as given in Fig. 3(b) (T = 40°C).

the database of viscoelastic material properties shown in Figs. 3(a and b). The measured values of complex shear modulus [Fig. 3(a)] and Poisson's ratio [Fig. 3(b)], which are appropriate for the temperature of 40°C, were chosen for the AC layer in this study.

A typical tandem axle carries a total axle load of 180 kN, and when wide-base tires are used the load carried by each tire is 45 kN/tire. On the other hand, when typical dual tire configuration is used, the tire load is 22.5 kN/tire. The two wheel configurations being considered by this study are shown in Fig. 6. The tire-pavement interaction stress distributions used in this study is based on the recent, most comprehensive work on wide-base tires carried out by the South African Institute of Road (Council of Scientific and Industrial Research) (De Beer et al. 1996). These researchers developed a device to measure all three components of tire-pavement contact stresses under a moving wide-base tire. They developed an advanced measuring system referred to as vehicle-road surface pressure transducer array (VRSPTA) that is capable of measuring vertical, transverse, and longitudinal contact stresses simultaneously under a moving tire. This system has undergone extensive calibration and has been shown to be robust and effective (De Beer et al. 1996).

Vertical σ_{zz}, longitudinal τ_{xz} and transverse τ_{yz} contact stresses reported by De Beer et al. (1996) for a Bridgestone wide-base 425/65R22.5 tire were used to represent the pavement surface loading required in (4*a*)–(4*c*). As a typical plot, the variation of σ_{zz} within the loaded area is shown in Fig. 7. This stress distribution was obtained for a vertical load of 45 kN with tire inflation pressure range varying between 850 and 900 kPa. It is clear that the contact pressure variation is nonuniform, and the loaded area is noncircular with maximum dimensions of about 32.0 and 16.0 cm in the transverse and longitudinal directions, respectively. The maximum σ_{zz} is much higher than the tire inflation pressure and is as much as 1,563 kPa. The longitudinal and transverse shear stresses also indicate nonuniform stress distributions but of much lower values. The maximum longitudinal and transverse shear stresses are 180 and 254 kPa, respectively. This means that the contact shear stresses are only about 12 and 16% of the maximum vertical stress.

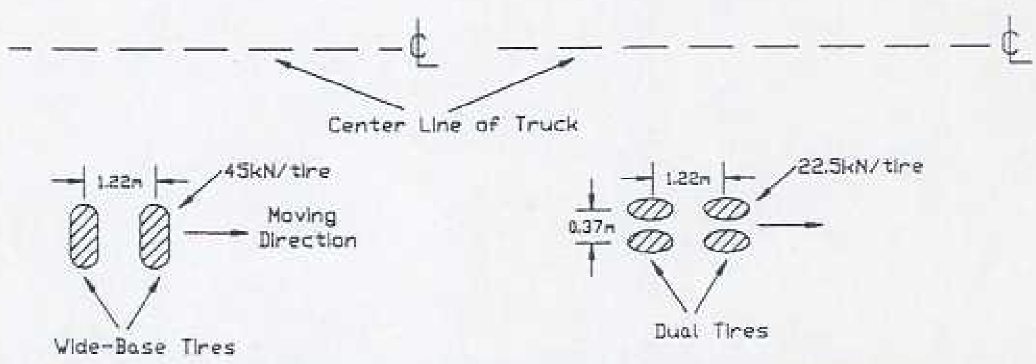

FIG. 6. Moving Tandem Axle with Wide-Base and Dual Tire Configurations

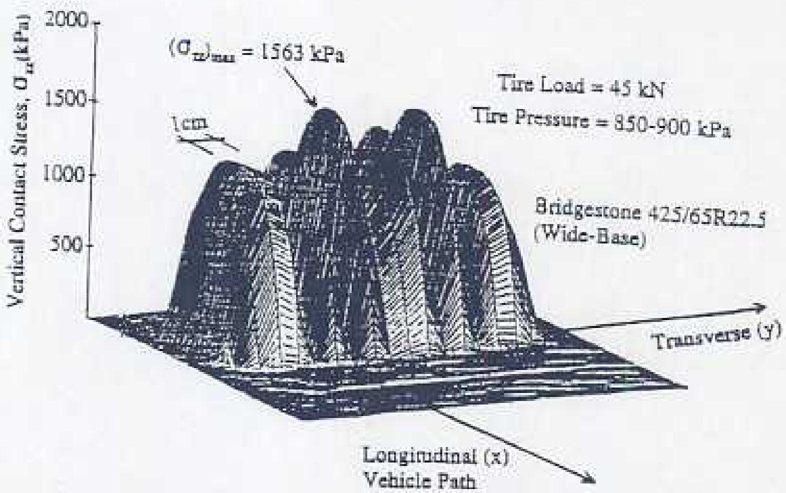

FIG. 7. Nonuniform Vertical Stress Distribution under Wide-Base Tire (after De Beer et al. 1996)

Results and Interpretation

Though 3D-MOVE can compute any response such as strain, stress, displacement, and acceleration at any point, only longitudinal tensile-strain response at the bottom of the AC layer ε_{AC} is reported in this paper. The response is computed at a location directly below the midpoint of the loaded area. This is because one of the most important performance indicators that is required in pavement distress evaluation is ε_{AC}. The program 3D-MOVE was used to obtain this parameter for both the thin and thick pavements identified earlier. Computed time-history response of ε_{AC} for both thin and thick pavements under tandem axle with wide-base tires moving at a speed of 72 km/h are shown in Fig. 8. The characteristics of the computed strain history are similar to those recorded in many field tests (Bonaquist 1992; Sebaaly and Tabatabaee 1993). There are two tensile-strain peaks that correspond to the presence of two loaded areas.

The following observations can be made from Fig. 8:

1. As expected, the ε_{AC} in the case of the thick pavement is much smaller, and it is ~53% of the strain in the thin pavement.
2. The pulse width of the strain from the load is somewhat higher for the thick pavement.
3. A closer look at the strain response indicates that there is a strong coupling between responses caused by the two loaded areas, and in the case of the thin pavement this is more evident.
4. A substantial compressive-strain component of as much as 25% of the maximum tensile value is computed for both pavements.

Fig. 9 shows the influence of vehicle speed on ε_{AC}. There is a significant reduction in the strain magnitude as the speed

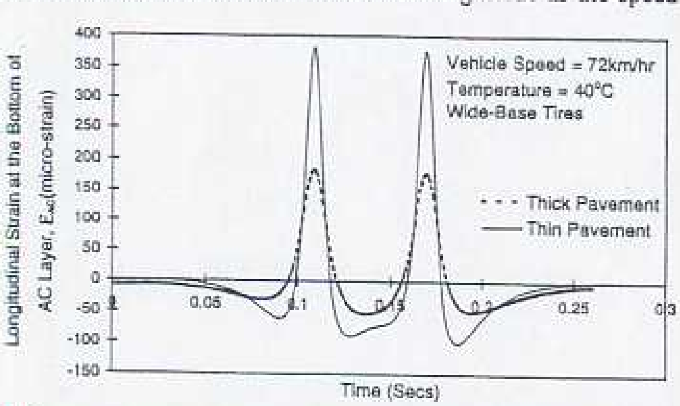

FIG. 8. Response History of ε_{AC} for Vehicle Moving at 72 km/h

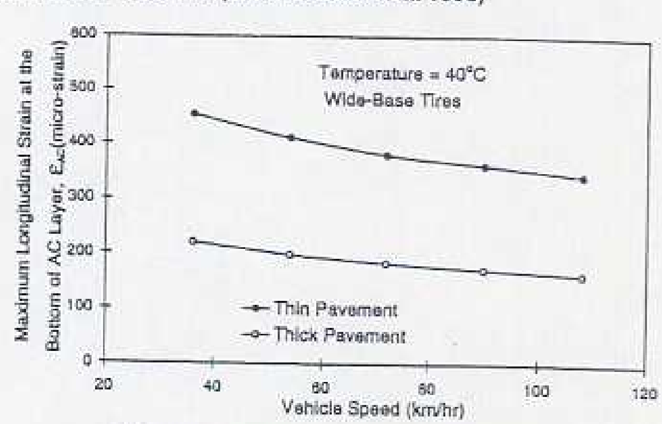

FIG. 9. Influence of Vehicle Speed on ε_{AC}

increases for both pavements. In the case of thin pavement, ε_{AC} reduces from 452μ to 350μ (a decrease of 23%), when the speed of the vehicle increased from 36 km/h to 108 km/h. The reduction in ε_{AC} for the case of thick pavement is somewhat higher (~33%). Such reductions in pavement response as the speed increases are significant and was observed first in full-scale field tests carried out by the Western Association of State Highway Officials in the 1950s. Subsequently, the same observations were made in other field measurements such as the American Association of State Highway and Transportation Officials road test (American 1962) and Pennsylvania State University road tests (Sebaaly and Tabatabaee 1993). In the latter case, direct measurements of longitudinal strain were made, and the reduction was as much as 50%. It may be noted that the field-measured strain responses include the influence of the dynamic (perturbation) load.

A few analytical studies have accounted for the variation of contact stresses (normal and shear) within the loaded area in the estimation of ε_{AC} (Tielking and Roberts 1987; Perdomo and Nokes 1993). In particular, the study of Perdomo and Nokes showed that inclusion of contact shear stresses is very important. They computed an increase in ε_{AC} of as much as a factor 6 when contact shear stresses are considered. Fig. 10 depicts the strain response ε_{AC} computed by 3D-MOVE with and without contact shear stresses. It is seen, contrary to the study of Perdomo and Nokes, that the influence of contact shear stresses on ε_{AC} is minimal. Many factors may be attributed to this discrepancy. First of all, Perdomo and Nokes used circular stationary loaded areas and a contact stress distribution that conformed to radial symmetry. The loaded area and contact stress distribution associated with the wide-base tires (Fig. 7) do not conform to the load description used by Perdomo and Nokes (1993). Secondly, they used a substantially higher

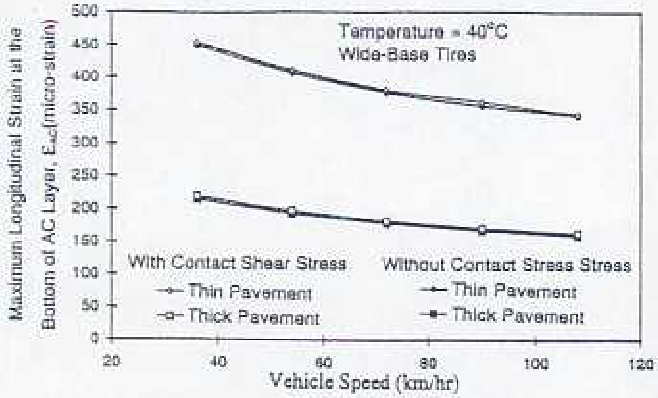

FIG. 10. Influence of Contact Shear Stresses on ε_{AC}

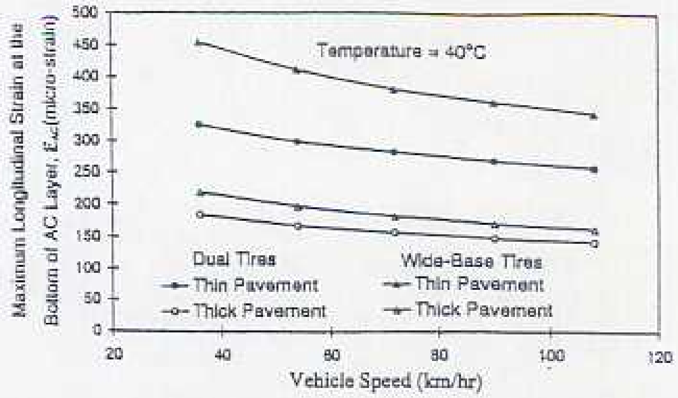

FIG. 11. Tensile Strain Response in AC from Wide-Base and Dual Tires as Function of Vehicle Speed

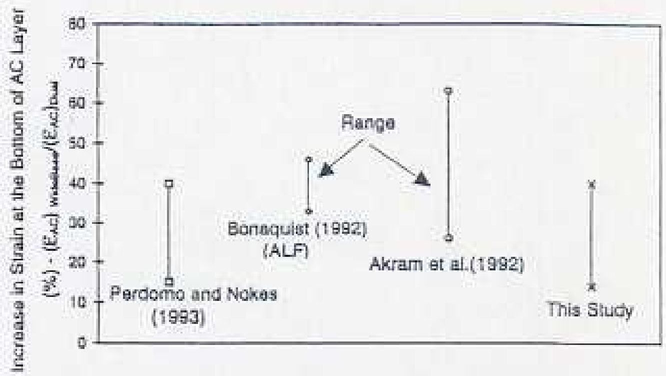

FIG. 12. Percent Increase in Normal Strain in Wide-Base Tires

radial shear stress distribution. The maximum radial shear stress was as much as 56% of the maximum normal stress. On the other hand, the maximum shear stresses (longitudinal and transverse) used in this study are only 12 and 16% of the maximum normal stress. It is believed that the shear stress distribution adopted in this study is more realistic as it is based on comprehensive field measurements made by the Council of Scientific and Industrial Research using a state-of-the-art technology.

The response caused by both wide-base tires and dual tires are needed to compare their influence on pavement distress. Fig. 11 shows strain component ε_{AC} for wide-base and dual tires. The contact area and stress distribution for dual tires were selected based on the work of Sebaaly (1992). The stress distributions that are appropriate for a load of 22.5 kN/tire and a tire inflation pressure of 862 kPa were used in the study. Since Sebaaly did not report on contact shear stresses they were not considered in the case of the dual tires. However, for the wide-base tires all three stress components were included.

It is clear from the figures that the strain response from the wide-base tires are significantly higher. At an intermediate speed of 72 km/h, the strain response ε_{AC} computed for wide-base tires on thin pavement is 33% higher than those computed for the dual tires. This increase reduces to 16% when the thick pavement is considered. There are many studies that have compared the strain component ε_{AC} between wide-base and dual tires. Results in terms of percent increase in ε_{AC} caused by wide-base tires over the dual tires reported by four studies are presented in Fig. 12. Results from this paper and the study by Perdomo and Nokes (1993) are analytical, while the studies by Akram et al. (1992) and Bonaquist (1992) are experimentally based. Care should be taken in interpreting this figure. It is because the conditions such as the layer thicknesses, material properties (or temperature), and tire pressure are not the same in these studies. It appears that although the results from this study are consistent with those given by Bonaquist (1992) and Perdomo and Nokes (1993), the range given by Akram et al. (1992) is much wider. It should be noted that in the experimental study of Akram et al. (1992), the tire inflation pressure for both types of tires was different. Furthermore, their study did not directly measure the strain ε_{AC}. They estimated ε_{AC} using the deflection bowl caused by the moving truck. Validity of this procedure is questionable since field tests by Sebaaly and Tabatabaee (1993) revealed that the relationship between pavement surface deflections and ε_{AC} is not consistent.

Modification to Load Perturbation

Thus far attention has been given to evaluate the strain response induced by the constant average axle load $\bar{P}$. However, when the perturbation of the axle load $P(x)$ is to be considered, the computed strain responses have to be modified. This perturbation of axle load has been characterized by many researchers, and an excellent summary of the state of the art has been compiled by Streit et al. (1995). Many studies, in particular the studies by Woodrooffe and LeBlanc (1986) and LeBlanc and Woodrooffe (1995), give the perturbation load in terms of dynamic load coefficient (DLC), which is defined as the ratio of the standard deviation of the perturbation load and average or nominal static wheel load. The DLC values are available as a function of road roughness, vehicle speed, and

TABLE 2. DLC Values for Different Tractor Suspensions (after Woodrooffe and LeBlanc 1986)

Vehicle speed (km/h)	TRACTOR SUSPENSION TYPE								
	Air Bag			Four Spring (Leaf Spring)			Rubber Spring Walking Beam		
	Smooth road	Average road	Rough road	Smooth road	Average road	Rough road	Smooth road	Average road	Rough road
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
40	0.03	0.04	0.05	0.04	0.05	0.08	0.04	0.08	0.08
60	0.04	0.06	0.08	0.04	0.08	0.09	0.04	0.08	0.11
80	0.05	0.09	0.10	0.07	0.13	—*	0.07	0.22	0.25

*Data not available.

vehicle suspension system. These values, inferred from Woodrooffe and LeBlanc (1986) and LeBlanc and Woodrooffe (1995), are given in Table 2.

The coefficient DLC along with strain responses computed thus far can be used to estimate the strain variability resulting from the perturbation load. Using (3), the standard deviation σ_ε of the strain ε_{AC} can be evaluated as

$$\sigma_\varepsilon = \mathrm{DLC}^*\varepsilon_{AC} \quad (13)$$

in which ε_{AC} is the strains given in Figs. 8–11; and the coefficient DLC is given in Table 2. The σ_ε values provide an approximate estimate of the variability of ε_{AC}.

SUMMARY AND CONCLUSIONS

This paper describes a more realistic model for evaluating pavement response to moving traffic loading. The proposed model handles actual traffic loading conditions with due considerations given to important factors such as the vehicle speed, the dynamic load variations, and the nonuniform stress distributions at the tire-pavement interface. The applicability of the proposed approach and the ensuing computer program has been verified using three existing classical solutions. Based on the analysis presented in this paper, the following conclusions can be made:

1. Traffic loads result in stress distributions (normal and shear) at the tire-pavement interface that are nonuniform. The proposed model is capable of handling any specified stress distributions.
2. The proposed model was able to identify that the impact of vehicle speed on the tensile strain at the bottom of the AC layer is in a manner consistent with several field studies. Many of the mechanistic pavement response models are deficient since they do not include vehicle speed as a governing factor.
3. The inclusion of contact shear stresses (longitudinal and transverse) did not significantly influence the tensile strain at the bottom of the AC layer ε_{AC}. Other studies showed greater impact from contact shear stresses because those studies assumed unrealistic shear stress distributions.
4. An important application of the proposed approach has been illustrated by comparing pavement strain responses computed with wide-base tires and dual tires. At an intermediate speed of 72 km/h, the strain response ε_{AC} computed for wide-base tires on a thin pavement is 33% higher than those computed for the dual tires. This increase reduces to 16% when a thick pavement is considered.
5. This paper also presents a simplified procedure to account for the dynamically varying (space and time) tire-pavement interaction load, thus enabling pavement engineers to assess the strain response of pavements in terms of road roughness, truck suspension system, and vehicle speed.

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